Cover page

Title: Permanently Installable, Active Guided-Wave Sensor for Structural Health Monitoring

Authors: Hegeon Kwun
Glenn M. Light
Sang Kim
Ron H. Peterson
Robert L. Spinks

## ABSTRACT

An active guided-wave sensor is described that can be used for periodic and long-term inspection and monitoring of structures for structural degradation such as crack formation and growth and corrosion material loss. The sensor, based on the magnetostrictive sensor technology developed and patented by Southwest Research Institute™ (SwRI™), is low-profiled, inexpensive, and permanently attachable to structural surface. The sensor can inspect and monitor large areas of a structure and provide quantitative information on the condition of the structure. By multiplexing multiple sensors installed at strategic locations on a large structure (such as airplane, ship, bridge, offshore platform, large storage tank, building, etc.) from a single data acquisition station, the entire structure can be quickly inspected for damaged areas and trending that are needed for structural integrity assessment and determination of remedial action if necessary. Experimental data showing the sensor's applicability to structural health monitoring of large plate structures are given.

## INTRODUCTION

To reduce operating and maintenance costs of structures and at the same time to enhance their safety and reliability and to minimize downtime, development of suitable structural health monitoring (SHM) technologies for diagnostics and prognostics on primary load carrying structural system components is necessary [1].

There are two types of sensors considered for SHM applications. One type is passive such as fiber optics, stain gauges, thermometers, accelerometers, and acoustic emission. The other type is active such as ultrasonic, eddy current, and guided waves.

---

Hegeon Kwun, Glenn M. Light, Sang Kim, Ron H. Peterson, and Robert L. Spinks, Southwest Research Institute, 6220 Culebra Road, San Antonio, Texas 78238-5166 — hkwun@swri.org

The passive sensors detect environmental conditions the structure is subjected to and the resulting structural responses. The data from passive sensors are then used to infer the integrity and safety of the structure.

When actuated, the active sensors inspect the structure and detect and locate actual damage in the structure (such as cracking, erosion and corrosion). Since the active sensors provide data directly linked to structural condition, they are preferred for the SHM applications. Of the active sensors, the guided wave sensors are ideal because guided waves can travel a long distance and a large area of the structure can be remotely interrogated and monitored by using the sensor (instead of spot monitoring by other active sensors) [2-4].

For application to active SHM, SwRI™ has recently developed a thin-strip, guided-wave sensor based on the magnetostrictive sensor (MsS) technology developed and patented by SwRI [5]. The sensor is thin, lightweight, surface-mounted, durable, and inexpensive to build. The sensor therefore has high potential for practical applications.

In this paper, the technical background on the thin-strip MsS guided-wave sensor for SHM is described followed by an example of its application to SHM of plate structures for monitoring of corrosion and weld cracks, multiplexing approach for multiple distributed sensors, conclusions, and recommendations for further work.

## TECHNICAL BACKGROUND

Figure 1 schematically illustrates the MsS guided-wave sensor designed for SHM of plate-type structural components. The sensor, which is a variation of the MsS plate probe [3], consists of a thin strip of ferromagnetic material (typically nickel) and a coil in thin printed circuit board placed over the strip. Actual proto-type sensors contain two coils for control of wave propagation direction.

Much like a strain gauge, the sensor is permanently bonded to the surface of a structure under monitoring with appropriate adhesive such as epoxy. The ferromagnetic strip is magnetically conditioned to provide DC bias magnetization necessary for MsS operation. When activated by supplying an rf electrical current pulse to the sensor coils by using the MsS instrument, the coil generates shear-horizontal guided waves in the ferromagnetic strip via the magnetostrictive effects. The generated guided waves, in turn, are coupled to the structure and propagate along the structure for interrogation. The direction of the wave propagation is perpendicular to the length-wise direction of the sensor that acts like a line source (or detector) [6]. The sensor also detects signals that are reflected back from the structural geometric discontinuities and defects, in the same manner used for long-range guided-wave inspection [2-4].

For SHM, the inspection data are periodically collected and compared to the baseline data established at the time of sensor installation. Because the sensor is remained fixed, the data comparison allows trending of the structural condition changes and a quick detection of damages and their locations that have occurred in the structure over that time for assessment of the structural condition and determination of subsequent actions needed. Since guided waves can travel a long distance in the

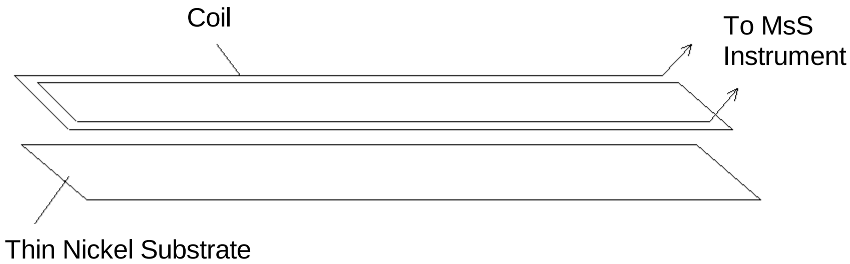



***Fig. 1. Illustration of the thin-strip MsS guided-wave sensor for structural health monitor ing. The coil is placed directly on the nickel layer.***

structure, a large area of the structure can be economically interrogated and monitored in this manner.

## EXAMPLE OF APPLICATION – SHM OF PLATE STRUCTURES

### Objective

There are a variety of large structures that are composed of plates joined together. Examples include ships, above or under ground storage tanks, containment liners in nuclear power plants, steel bridges, and steel columns in high risers. The principal defects that are developed in these structures in service are loss of material wall thickness by corrosion and cracking. Corrosion may be localized or present over large areas. Cracking may occur at high stress concentration areas and at welded joint.

If the defects go unchecked, they will ultimately lead to failures of these large structures consequent of which could be catastrophic. To ensure their safety and structural integrity, inspections are performed on these structures. Because of the large areas to cover and preparations needed for inspection access, inspection of such structures is time consuming and expensive. Cost-effective and economical maintenance of these large structures could be achieved by applying a suitable SHM method with active sensors that can inspect and monitor large areas of the structure from a fixed installation location.

The experimental investigation described in this section was conducted to show the feasibility of active SHM of a large area of a plate structure by using the thin-strip MsS guided-wave sensor.

### Experimental Arrangement and Procedures

Figure 2 illustrates the configuration of test plate and setup used in the experimental investigation. The test plate sample was 6.45-mm thick and approximately 1.22-m x 12.19-m in overall size. It was made by full-penetration welding two carbon steel plates. Two 20-cm-long, thin-strip, sensors were adhesively bonded to the test sample at approximately 3.66-m distance from end 1 as illustrated in Figure 2.

Using the sensors and MsS instrument (Model 2020) [7], 128-kHz shear horizontal guided waves were launched toward the end 2 of the test plate and the resulting signals reflected back from the geometric discontinuities were detected.

In simulation of SHM, baseline data were first acquired from the test sample using both sensors. Then the data were acquired periodically after placing a simulated defect in the central area of the guided wave beam of each sensor; for sensor 1, notch in the weld simulating weld cracking and for sensor 2, 6.35-mm-diameter and 50%-thickness-deep, drilled hole at 10.67-m from end 1 of the test plate simulating corrosion pits. The periodic data acquisition was repeated while incrementing the defect size; for the notch, up to 50-mm-long and 50%-thickness-deep and for the corrosion, up to 5 drilled holes as shown in Figure 3.

The periodically acquired data were then compared with the baseline data by using a signal differential algorithm developed by SwRI.

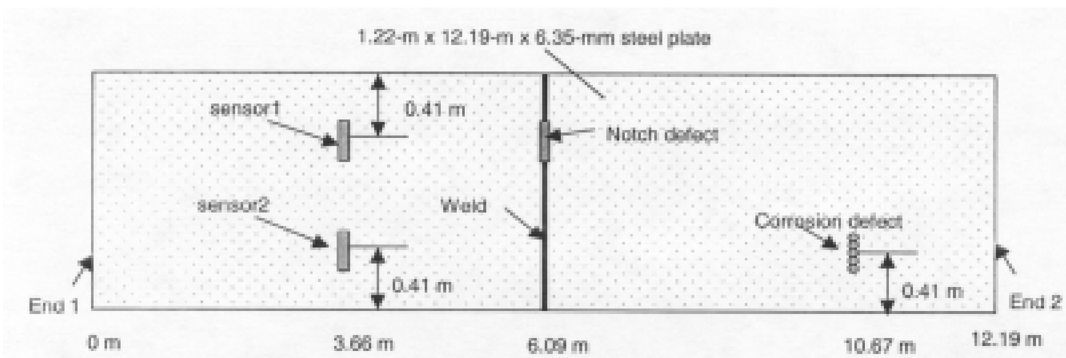
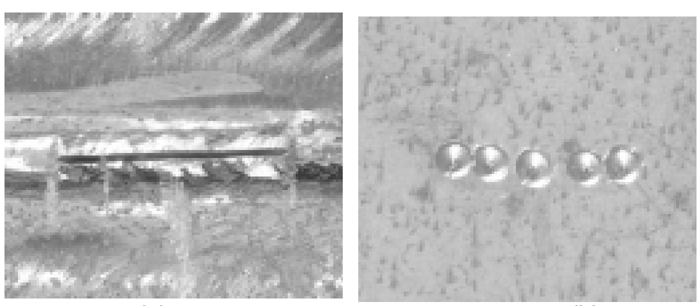



*Figure 2. Configuration of test plate and setup*



(a) (b)

*Figure 3. Photographs of simulated defects: (a) 50-mm-long, 50%-thickness-deep notch and (b) 6.35-mm-diameter, 50%-thickness-deep drilled holes*

## Experimental Results and Discussion

Figure 4 shows a series of periodically acquired data (in 1 volt/division scale) with sensor 1 before and after placing a notch in the weld and incrementing the notch size up to 50-mm-long and 50%-thickness-deep. The corresponding differential data in 0.2 volt/division scale are shown in Figure 5 that were obtained by subtracting the baseline data from the periodically acquired data. In these figures, signals reflected from the weld and end 2 are indicated as W and E2, respectively. Signals coming from the side opposite to the inspection side of the sensor due to imperfect wave direction control are indicated in parenthesis; for example, (E1) and (WE1) where WE1 indicates the weld signal reflected back from end 1.

The data in Figure 4 showed that the amplitude of the weld signal decreased with increasing notch size. The signal reflected from the notch should have opposite phase to the signal reflected from the weld and, therefore, destructively interfere. The observed decrease in the weld signal was caused by this destructive interference and increased notch signal amplitude with increasing notch size. The differential data in Figure 5 showed the increased changes in the weld signal with increasing notch size, indicating the feasibility of detecting weld cracking during SHM.

Figure 6 shows a series of periodically acquired data with sensor 2 before and after placing a 6.35-mm-diameter and 50%-thickness-deep drilled hole and increasing their numbers up to 5. The corresponding differential data in 0.05 volt/division scale are shown in Figure 7.

As can be seen in Figures 6 and 7, the drilled-hole signal was readily detectable when the number of drilled hole was three or more despite of the facts that the defects were 7-m away from the sensor location and small in size. The data in these figures clearly demonstrated the ability of the active guided-wave sensor to inspect and monitor a large area of plate structure for detection of defects and their growth.

The differential data in Figure 7 also showed that the signals from geometric features in the structure such as welds and ends could not be completely subtracted out and their amplitude varied. This would induce error in detecting the presence of defects and their growth in or very near to these geometric features; for example, weld cracking. More work is therefore needed on development of suitable calibration procedures and better signal processing techniques to further improve SHM capability.

The drilled holes were not detectable in the data obtained with sensor 1, indicating that the width of monitoring area of the sensor was relatively narrow even at the 7-m distance from the sensor. Further theoretical and experimental studies are recommended to establish the relationship between the sensor length, wave frequency, and the monitoring area.

## CONCLUSIONS

Conclusions that can be drawn from the test results described in this paper include:

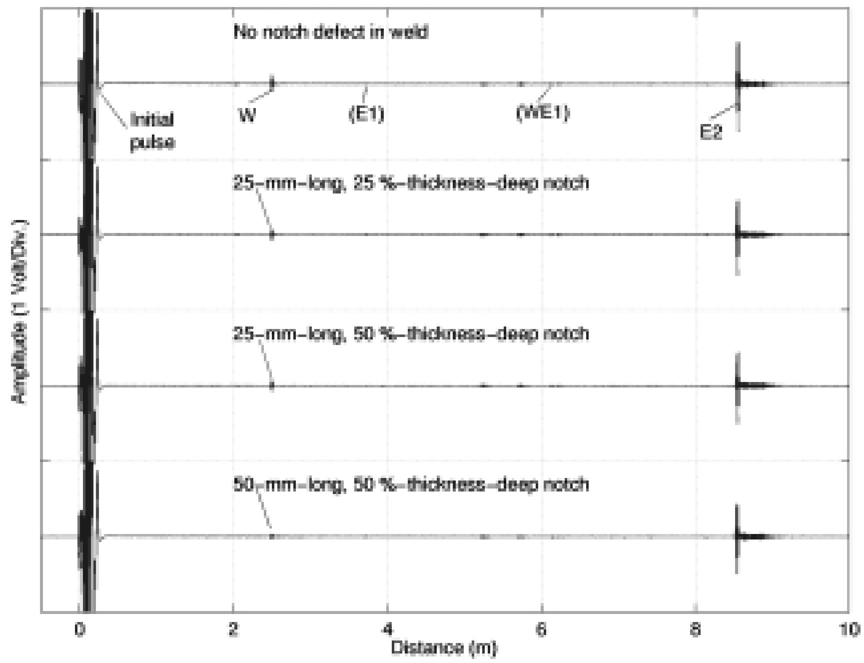



***Figure 4. Series of periodically acquired data with sensor 1 in simulation of monitoring of weld cracking***

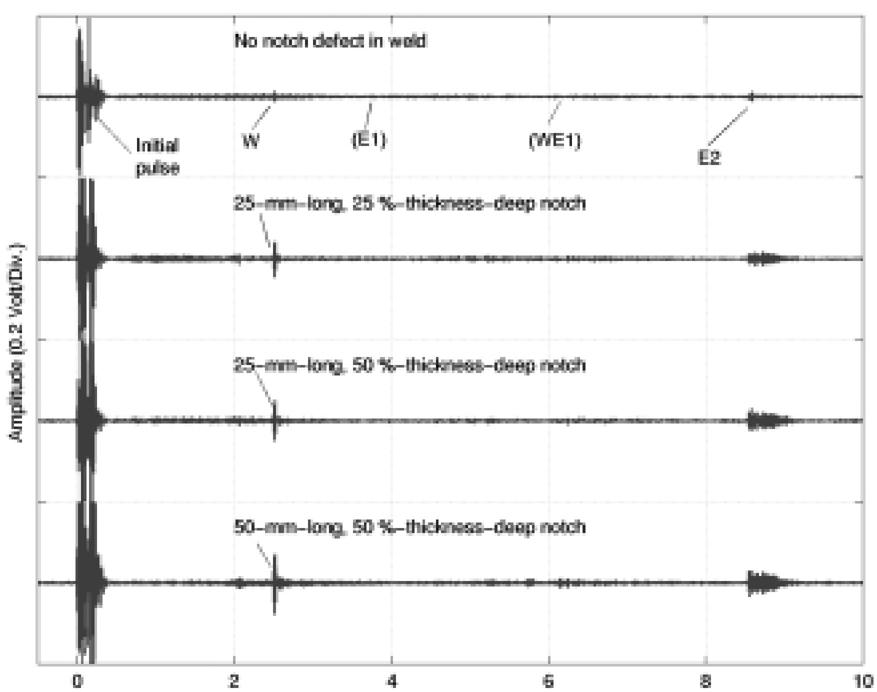



***Figure 5. Differential data of the data in Figure 4 obtained by subtracting baseline data from them in the monitoring mode***

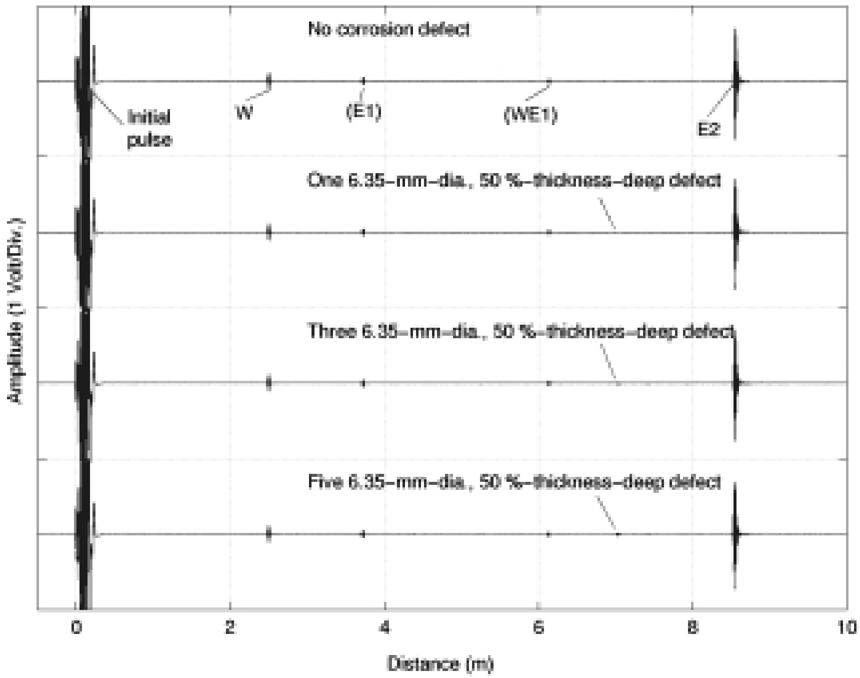



***Figure 6. Series of periodically acquired data with sensor 2 in simulation of monitoring of corrosion defefcts***

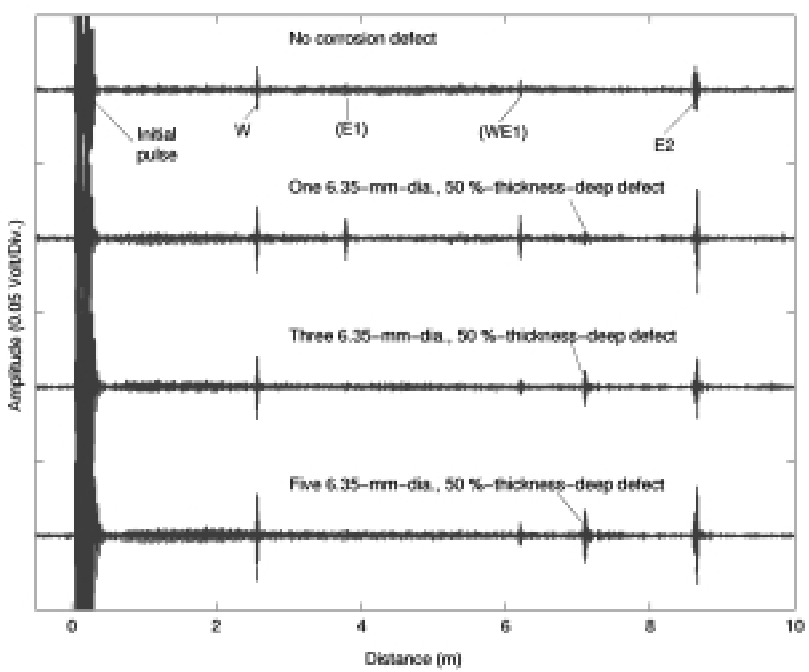



***Figure 7. Differential data of data in Figure 6 obtained by subtracting baseline data from them in the monitoring mode***

(1) Active SHM of a large area (several feet) of plate structure is feasible by using the thin-strip MsS guided-wave sensor.
(2) Defects such as weld-cracking and corrosion wall-loss area and their growth with time can be detected and monitored by using the active MsS-SHM approach.
(3) The thin-strip MsS guided-wave sensor is low-profiled, lightweight, surface-mounted, durable, and inexpensive, and therefore has high potential for practical use.

For practical implementation of the MsS guided-wave sensor for long-term SHM, further research and development of the sensor are recommended in the following areas:

(1) The long-term stability of the sensor in the operating environment of the structure under monitoring.
(2) The extent of its application—types of structures, monitoring range, and sensitivity of monitoring.
(3) Data processing methods for enhanced monitoring capability.
(4) Procedures for implementation and multiple sensor control.
(5) Field evaluation and test.

## ACKNOWLEDGEMENTS

The work described in this paper was supported by SwRI.

## REFERENCES

1. Chang, F.K. 2001. "Structural Health Monitoring—The Demands and Challenges," *Proceedings of the 3rd International Workshop on Structural Health Monitoring*, held at Stanford University, CRC Press, Boca Raton, Florida.
2. Alleyne, D.N., B. Pavlakovic, M. J. S. Lowe, and P. Cawley. 2001. "Rapid Long-Range Inspection of Chemical Plant Pipework Using Guided Waves," *Insight* **43**: 93–96.
3. Kwun, H., S. Y. Kim, and G. M. Light. 2001. "Long-Range Guided Wave Inspection of Structures Using the Magnetostrictive Sensor," *J. Korean Soc. NDT* **21**: 383–390.
4. Rose, J. L. 2002. "Standing on the Shoulders of Giants: An Example of Guided Wave Inspection," *Mat. Eval.* **60**: 53–59.
5. U.S. Patent Nos. 5,456,113, 5,457,994, 5,581,037, 5,767,766, 6,212,944, 6,294,912, and pending patents.
6. Kwun, H. and S. Y. Kim, "Magnetostrictive Sensor for Generating and Detecting Plate Guided Waves" (to be published).
7. Technical information can be found at www.mkckorea.com.